Using Smartphones to Identify Dynamic Characteristics of Timber Bridges

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Summary

This paper presents the preliminarily outcomes of a joint pilot project between the University of Bath and the University of California, Berkeley, and aims to demonstrate the feasibility of implementing the Smartphone as a device for the system identification of timber bridges. Two timber bridges were selected for vibration measurement, Black Dog Bridge in the UK and Knight Ferry Covered Bridge in the United States. To ensure the reliability of the data, a Smartphone was calibrated on a shaking table in the laboratory before measuring onsite. Two vibration tests were carried out on both bridges, these being free vibration and ambient vibration tests. The results were then analysed in both time and frequency domains. This paper also demonstrates the feasibility of Smartphones being used to identify the dynamic properties of timber bridges.

1 Introduction

Timber is a bio-degradable material that, for public safety structural health monitoring, is becoming an important technique to ensure the long term structural integrity of timber bridges. A number of health monitoring methods have been reported. For example, Tannert, Müller and Vogel used Non-destructive Testing methods (NDT), including core drilling and drilling resistance, to investigate the local condition of timber within a bridge, and monitored the moisture content of the timber members in the long term [1]. This project was limited to investigating the condition of individual members and obtaining material conditions where the NDT techniques were applied. Unlike NDT, limited to detecting local damage, deflection reflects how a timber bridge performs at the structural system level. Long term deformation due to creep and moisture content variation were investigated by using fibre optic sensors and GPS system and the outcomes compared with those obtained from conventional tri-axial accelerometers [2]. However, this still limits the engineers to analysing the structural integrity of timber bridges from static loading. With the system identification (SI) of timber bridges it is important for engineers not only to understand the dynamic properties of the structure they have designed, but also to be able to assess the structural health of a timber bridge.

Vibration measurements on infrastructures, in particular steel and concrete bridges, have been widely used to analyse the dynamic properties of the structures and assess their structural health in Europe and the United States [3-5]. Most of these measure the traffic-induced or ambient vibrations of concrete and steel bridges. Timber bridges are more flexible and therefore more suitable for vibration=based structural health monitoring methods to assess their conditions. Several projects have reported the assessment of the structural integrity of timber bridges by vibration measurements in which they were excited by instrumented hammer [6] or vehicles [7]. These vibration based structural health monitoring techniques normally require installing accelerometers on the structures. However, installing the conventional cabled sensors, in particular with high density sensor networks, has put industry and academics off due to the cost of the equipment itself and the installation of the coaxial cables. In the late 1990s, wireless sensors integrated with radio were proposed which substantially reduced the cost of the structural monitoring systems [8]. Since then, wireless sensors have quickly developed as a viable solution for structural health monitoring purposes [9].

2 Selection of Smartphones

Different makes and models implement different hardware and software, which leads to variations in the efficiency and suitability of Smartphones used as vibration measurement sensors. The parameters that need to be considered include: (1) sensitivity of accelerometer; (2) sampling rate; and (3) computational capacity. Table 1 summarises a variety of makes and models of off-the-shelf Smartphones. With the rapid development of Smartphones, computational capacity has become less of an issue. From Table 1 we can see that the Samsung Galaxy

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S IV has the best combined sensitivity and sampling capacity performance and hence in this project it was chosen as the sensor for vibration measurement of timber bridges.

Table 1 Technical data of Smartphones

Make and model	Sensitivity of accelerometer	Sampling rate
Samsung Galaxy S III	0.0006 m/s^2	100 Hz
Samsung Galaxy S IV	0.0006 m/s^2	100 Hz
HTC Sensation	0.0383 m/s^2	50 Hz
HTC One X	0.0120 m/s^2	100 Hz
Motorola Droid Razr HD	0.0012 m/s^2	125 Hz

3 Laboratory calibration

Before the tests, we calibrated the Smartphone on the Smart Shaking Table at the University of California, Berkeley (Figure 1). The Smartphone and an accelerometer were mounted on the structure on the shaking table. Two different tests were carried out, free vibration and forced vibration. The vibration signals captured by the accelerometer were compared with those captured by the Smartphone. It was observed that good agreement was found from the free vibration tests. However, high frequency noise was observed in the data from the Smartphone, which implies the need for appropriate filter techniques.

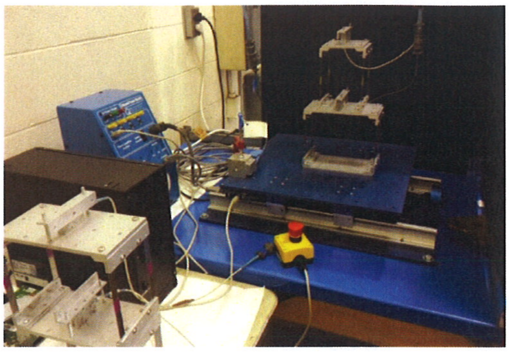

Figure 1 Smart shaking table for the Smartphone calibration

4 The bridges

In this paper, we have selected two bridges to measure the vibration, the Black dog Bridge in the UK and the Knight Ferry Covered Bridge in California, US. The Black Dog Bridge (Figure 2 and Figure 3) is located in Wiltshire, UK, one of the Millennium bridges in the area. The bridge spans 40 metres across the A4 road and is part of the National Cycle Network. It has a lightweight 2.1 metre width deck supported by a Glulam parabolic arch with a section of 675x675 mm and concrete foundations at both ends. The bridge is exposed to the environment with no protection from water and sun and therefore moderate bio-degradation was observed. The combined traffic and human induced vibration is the main source of the structural vibration of Black Dog Bridge.

Figure 2 Black Dog Bridge from the road

Figure 3 Black Dog Bridge from the deck

The Knight Ferry Covered Bridge (Figure 4 and Figure 5), a trussed and covered bridge, was completed in 1864, and is located in Stanislaus County, California. It features the longest covered bridge in California with a span of 100 metres, supported by two piers at both ends. The bridge is currently restricted to passenger access due to the discovery of structural safety issues, and has steel reinforcement. Its timber members are well protected by the cover.

Figure 4 Knight Ferry Covered Bridge from outside

Figure 5 Walkway of Knight Ferry Covered Bridge

5 Vibration measurement

Two different types of tests were carried out, i.e. free vibration and ambient vibration. At the Knight Ferry Covered Bridge, the Smartphone was placed at the middle of the largest span so as to capture the largest vibration signal. Excitation was then generated by a person weighing approximately 100 kg jumping on the bridge, and free vibration was measured for 2 minutes. Then a new measurement was started at the same location and measured the ambient vibration of the bridge for 30 minutes. When measuring the vibration of Black Dog Bridge, both conventional vibration measurement system and a Smartphone were used so as to compare the results. Both sensors and Smartphone were placed in the middle of the span, free and ambient vibrations of the bridge were then measured using the same procedure.

6 Results and Discussions

Black Dog Bridge

Figure 6 compares the time history data obtained form both accelerometers and Smartphones. It shows that the acceleration captured by Smartphone was smaller than that obtained from accelerometers. Fast Furiour Transform (FFT) was applied to investigate dynamic properties in the frequency domain. The natural frequency of the Black Dog Bridge, calculated from the time history record captured by acclerometers is 2.44Hz with damping ratio of 2.6%, compared with 2.44Hz with damping ratio of 3.3% from Smartphone. The analyses in frequency domain shows that it is more difficult to simply use a peak picking method due to the fact that the Smartphone data shows significant noise in high frequency as can be seen in Figure 7. The ambient vibration data of vertical movement of Black Dog Bridge is shown in Figure 8, and Figure 9 shows the FFT spectra of the ambient vibration data. It is obvious that the frequency domain technique is not suitable to analyse the ambient vibration data of the bridge as captured by the Smartphone. It is therefore proposed to use the time domain technique to obtain ambient vibration data.

Random Decrement Technique was implemented on the time-history records of ambient vibration of the Black Dog Bridge obtained from both accelerometers and Smartphone as shown in Figure 10 and Figure 11. Ibrahim time domain (ITD) method was then applied to determine the corresponding dynamic properties. The natural frequency and damping ratio from acclerometers calculated by ITD are 2.49Hz and 3.18%, whereas those from Smartphone are 2.49Hz and 3.32%, respectively. It shows good agreement between natural frequency and damping ratio obtained from both acclerometers and Smartphone.

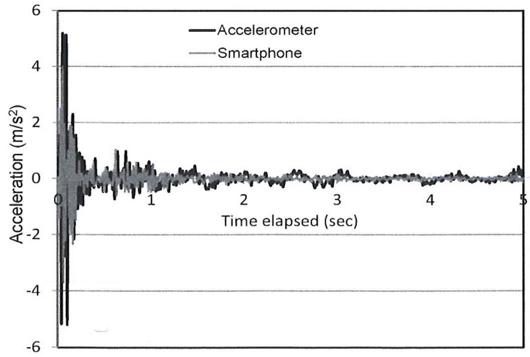

Figure 6 Comparison of free decay signal from accelerometer and Smartphone

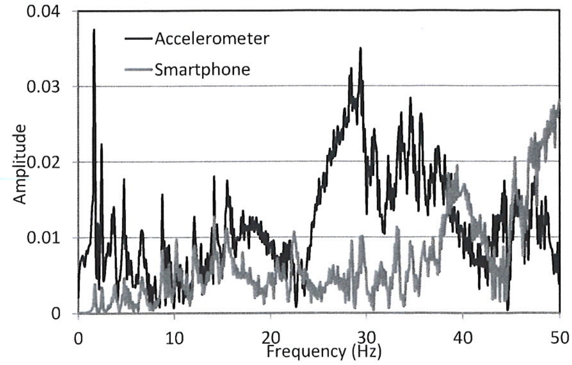

Figure 7 Comparison of frequency spectra of free decay signal

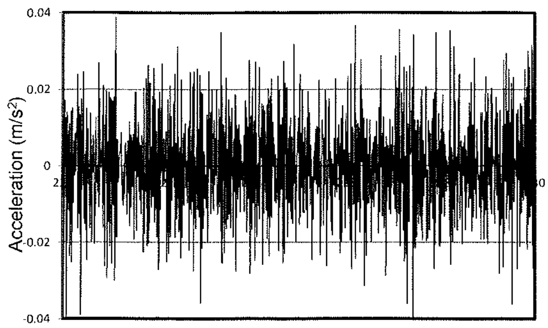

Figure 8 Time history record of ambient vibration of Black Dog Bridge captured by Smartphone

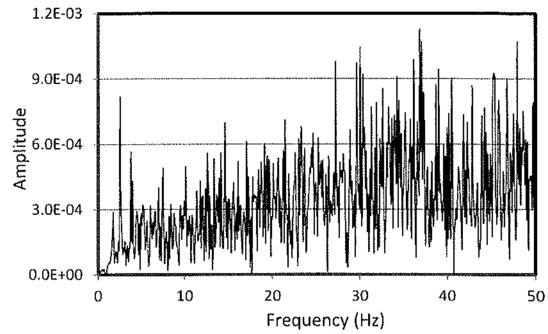

Figure 9 Spectra of time history record of ambient vibration of Black Dog Bridge captured by Smartphone

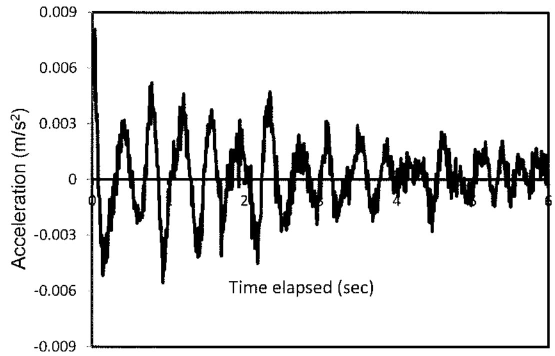

Figure 10 Random decrement signature of accelerometer recorded data

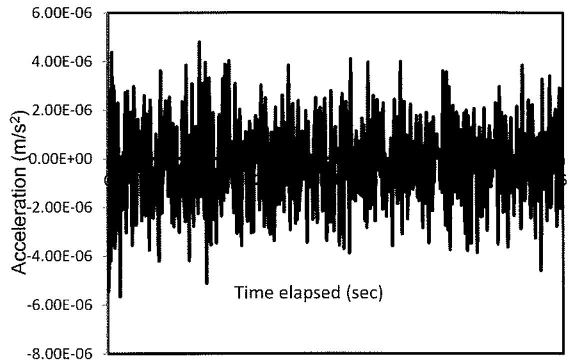

Figure 11 Random decrement signature of accelerometer recorded data

Knight Ferry Covered Bridge

From reuslts at Black Dog Bridge, it can be shown that using Smartphone is a reliable method for system identification, and good agreement has been shown when comparing the results obtained from both accelerometers and the Smartphone. This study also uses the same device to measure the dynamic properties of Knight Ferry Covered Bridge. Two methods were employed to analyse the vibration signal. Frequency domain technique was applied to the forced vibraton record, whereas time domain technique was applied to the random decrement signature of ambient vibration of the bridge. Figure 12 shows the free vibration signal of Knight Ferry Covered Bridge, which was used to identify the natural frequency of the structure in frequency domain. To analyse the ambient vibration of the two bridges, random decrement technique was applied as shown in Figure 13. The results are tabulated in Table 2. Good agreement was found in dynamic properties of Knight Ferry Covered Bridge analysed from both time domain and frequency domain methods.

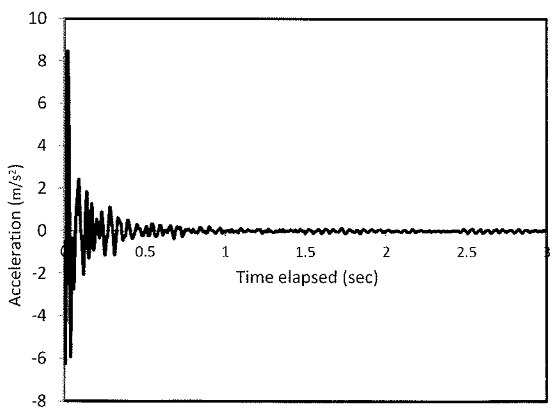

Figure 12 Free vertical vibration decay curve of vertical movement of Knight Ferry cover Bridge captured by the Smartphone

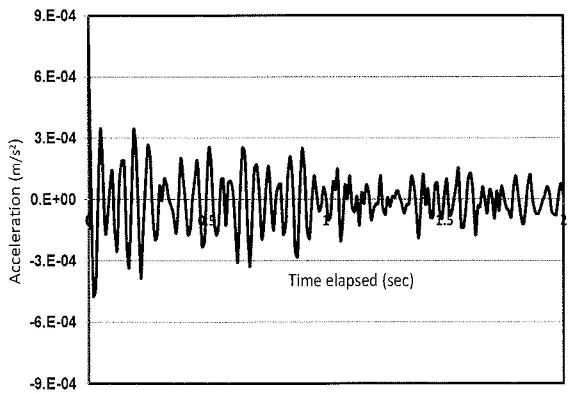

Figure 13 Random decrement signature of vertical movement of Knight Ferry cover Bridge captured by the Smartphone

Table 2 Comparison of dynamic properties analysed from time and frequency domains method

	Natural frequency (Hz)	Damping Ratio
Time domain	3.86	1.8%
Frequency domain	3.71	2.8%

7 Conclusions

In this paper, we propose to use an off the shelf Smartphone as an alternative to the conventional vibration measurement facility, which would normally include a number of accelerometers connected to data acquisition systems by coaxial cables. The ambient and forced vibrations of two bridges were measured, comparisons on the results analysed from both frequency and time domains were made. The following conclusions can be drawn from this project:

(1) When choosing the Smartphones to measure the vibrations, the sensitivity of the accelerometer and maximum sampling rate should be considered.
(2) When an appropriate Smartphone is chosen, it can be a feasible alternative to measure forced vibration.
(3) Time domain analyses are suitable to analyse the ambient vibration of bridges.

References

[1] Tannert, T., A. Müller, and M. Vogel, Structural health monitoring of timber bridges, in International Conference on Timber Bridges 2010. 2010: Lillehammer, Norway. p. 205-212.

[2] Gustafsson, A., A. Pousette, and N. Björngrim, Health monitoring of timber bridges, in International Conference on Timber Bridges. 2010: Lillehammer, Norway. p. 213-222.

[3] Andersen, E. and L. Pedersen, Structural monitoring of the great belt east bridge. Strait crossings, 1994. **94**: p. 189-95.

[4] Brownjohn, J., et al., Lessons from monitoring the performance of highway bridges. Structural Control and Health Monitoring, 2005. **12**(3-4): p. 227-244.

[5] Pines, D. and A.E. Aktan, Status of structural health monitoring of long-span bridges in the United States. Progress in Structural Engineering and materials, 2002. **4**(4): p. 372-380.

[6] Crews, K., B. Samali, and J. Li. Reliable assessment of aged timber bridges using dynamic procedures. in The 8th World Conference on Timber Engineering. 2004.

[7] Wang, X., et al., Nondestructive assessment of single-span timber bridges using a vibration-based method, in FPL-RP-627. 2005: Madison, WI.

[8] Straser, E.G. and A.S. Kiremidjian, A modular, wireless damage monitoring system for structures. 1998, John A. Blume Earthquake Engineering Center, Stanford University: Stanford, CA.

[9] Lynch, J.P., An overview of wireless structural health monitoring for civil structures. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2007. **365**(1851): p. 345-372.

[10] Thompson, C., et al., Using Smartphones to detect car accidents and provide situational awareness to emergency responders, in Mobile Wireless Middleware, Operating Systems, and Applications. 2010, Springer. p. 29-42.

[11] White, J., et al., WreckWatch: automatic traffic accident detection and notification with Smartphones. Mobile Networks and Applications, 2011. **16**(3): p. 285-303.

[12] Kotsakos, D., et al., SmartMonitor: using smart devices to perform structural health monitoring. Proceedings of the VLDB Endowment, 2013. **6**(12): p. 1282-1285.

[13] Nanayakkara, A., The Feasibility of a Smartphone Application to Successfully Measure the Natural Frequency and Damping Ratio of Timber Floors, in Department of Architecture and Civil Engineering. 2014, University of Bath: Bath, UK.